Design of Stabilizing Arm Mechanisms for Carrying and Positioning Loads

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Stabilizing arm mechanisms are used to support and position a load with minimal force from the user. Further, stabilizing arm mechanisms enable operators to stabilize the motion of the load while walking or running over variable terrain. Although existing stabilizing arm mechanisms have reached fairly broad adoption over a range of applications, it remains unknown exactly how the spring properties and geometric parameters of the mechanism enable its overall performance. We developed a simplified model to analyze the vertical dynamics of stabilizing arms to determine how the spring properties and mechanism geometry affect the natural frequency of the load mass, the range of load masses that can be supported, and the equilibrium position of the load mass. We found that decreasing the unstretched spring free length is the most effective way to minimize the natural frequency; the spring lever arm can be used to adjust for a desired load mass range, and the linkage length can be used to adjust the range of motion of the stabilizing arm. The spring stiffness should be selected based on the other parameters. This work provides a systematic design study of how the parameters of a stabilizing arm mechanism affect its behavior and fundamental design principles that could be used to improve existing mechanisms, and enable the design of new mechanisms. [DOI: 10.1115/1.4030987]

1 Introduction

Stabilizing arm mechanisms are designed to have a low effective stiffness and damping to support and position a load about a desired static equilibrium position with minimal force input from the user [1]. They are also used as passive mechanical vibration isolators because they can achieve very low natural frequencies. For example, the Steadicam® "iso-elastic" stabilizing arm mechanism (The Tiffen Company, Hauppauge, NY) (Fig. 1) has a very low effective stiffness, and natural frequency which enables an operator to quasi-statically position and dynamically stabilize a camera Fig. 1 [2].

Although multiple stabilizing arm mechanisms have been successfully developed in the past [3–6], it is not presently known exactly how each of the important design parameters of a stabilizing arm mechanism affect the natural frequency of the load mass, the range of load masses that can be supported, and the vertical static equilibrium height of the load mass. This work provides a systematic design study of how the parameters of stabilizing arm mechanisms affect their behavior, and could enable the design of new mechanisms such as a highly compliant backpack or handle suspension for carrying heavy loads [7–12] and for supporting inherent or external payloads for legged robots [10,13,14].

2 Approach

2.1 Motion Assistance and Vibration Isolation. To assist an operator's motion, a stabilizing arm mechanism should have a low mechanical impedance. To isolate vibration and reject disturbances, a stabilizing arm mechanism should have a low natural frequency. Both of these objectives can be obtained in one system by achieving a low effective stiffness.

Mechanical impedance is the ratio of force divided by velocity and is a measure of the system's resistance to motion to an oscillating force [15]. The impedance for a single degree of freedom spring–mass–damper system in the frequency domain and its magnitude is

$$Z = C + Ms + \frac{K}{s} \tag{1}$$

$$|Z| = \sqrt{C^2 + \left(M\omega - \frac{K}{\omega}\right)^2} \tag{2}$$

The effective stiffness and damping should be minimized to reduce the magnitude of the mechanical impedance for a given mass and input frequency.

Stabilizing arm mechanisms such as the Steadicam are also effective vibration isolators. The human body center of mass bounces vertically during walking and can be approximated by a sinusoid with a frequency of ~2 Hz and a displacement of 3–7 cm [16–18]. The Steadicam® stabilizing arm mechanism can achieve a natural frequency significantly lower than 2 Hz, decoupling the motion of the camera from that of the operator's body (Fig. 1).

2.2 Low Natural Frequencies Lead to Large Static Deflections. In a linear spring–mass–damper system, the natural frequency is

$$\omega_n = \sqrt{\frac{K}{M}} \tag{3}$$

Statically, the load weight must be equal to the linear spring force

$$F = Mg = K\Delta x \tag{4}$$

The static spring deflection can then be related to the natural frequency

$$\Delta x = \frac{g}{\omega^2} \tag{5}$$

Minimizing the natural frequency significantly increases the effective static spring deflection (Fig. 2(*a*)). For example, achieving a natural frequency of 0.5 Hz requires a very large static spring deflection of ~1 m. Therefore, only long travel springs such as elastic cords could be used to minimize the natural frequency in a linear spring suspension system. This approach was used to support a 27 kg load with a ~0.7 Hz backpack suspension, which required an effective spring deflection of ~0.5 m [7,8,12].

Metal coil springs are well-understood, offer predictable performance, have low damping, and are cost effective, so they are a better spring choice to use in a suspension than a long travel elastic cord. However, conventional metal coil springs can only deflect a small distance, often less than ~10 cm for the mechanism scale presently considered [19,20]. The compact stabilizing arm mechanism effectively uses mechanical advantage to reduce the spring travel length and natural frequency of the suspension.

2.3 Stabilizing Arm Model. Here, we use a simplified physics-based model of a stabilizing arm mechanism based on the

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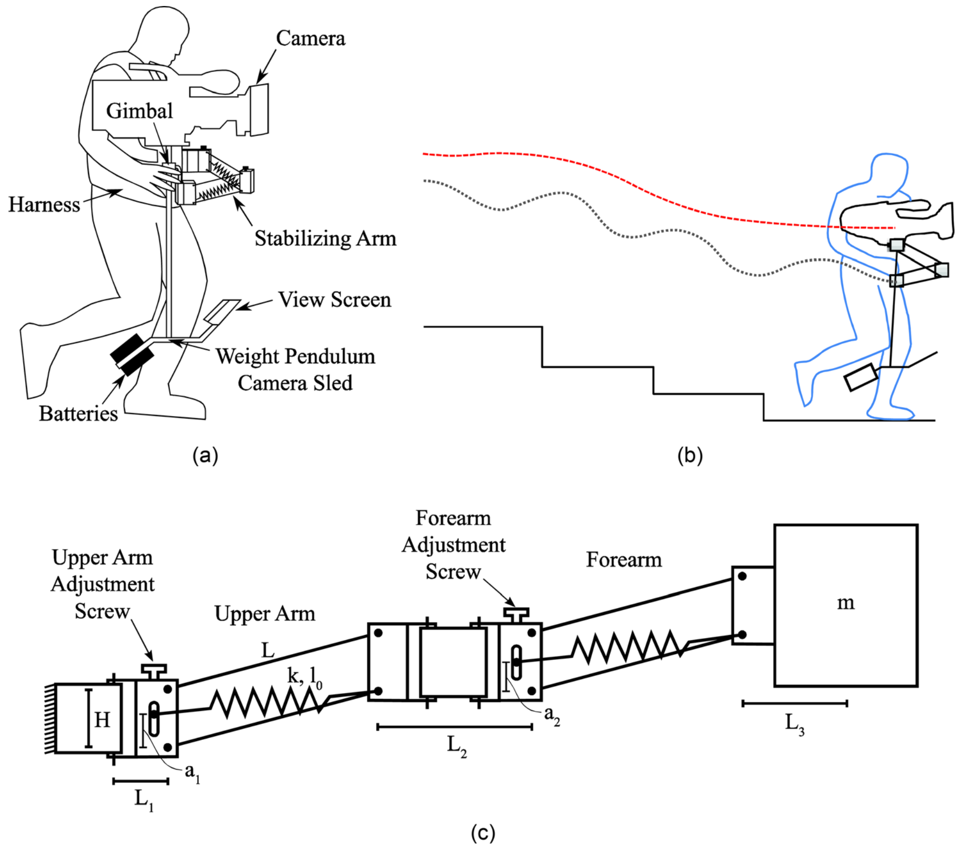

Fig. 1 The Steadicam® stabilizing arm (*c*) enables a camera and associated equipment to be positioned with minimal force from the operator [21] (*a*) and stabilizes the vertical motion of the camera during locomotion over flat ground and rough terrain (*b*)

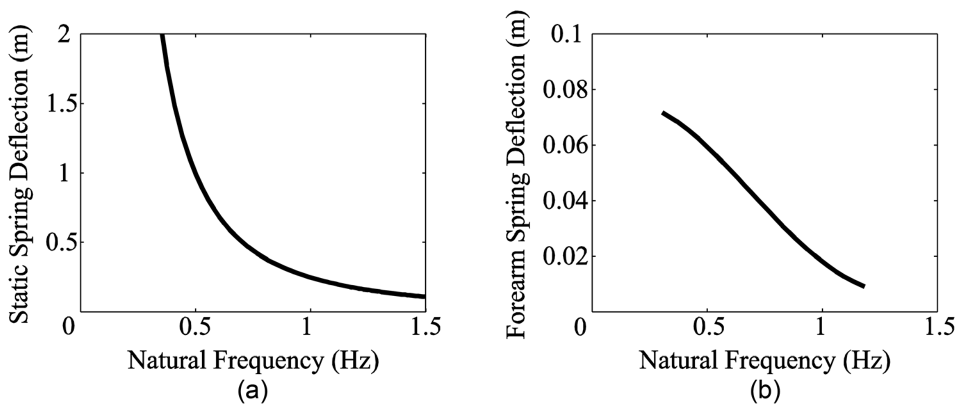

Fig. 2 In a linear spring suspension system, the effective static spring deflection increases substantially as the natural frequency is minimized (*a*). A stabilizing arm mechanism is able to achieve natural frequencies between 0.2 Hz and 1.2 Hz with relatively small static spring deflections below 0.0762 m, (*b*) when the load mass was varied from 1.81 kg to 13.6 kg with the highest forearm lift adjustment value ($a_2 = 0.0394$ m).

Steadicam® iso-elastic arm (Fig. 1(*c*)) to study the effects of the spring stiffness k, spring lever arm a, linkage length L, and spring free length l_0 on the natural frequency and vertical static equilibrium position of the system for a range of load masses. We created this model using the SOLIDWORKS motion analysis package powered by ADAMS (SolidWorks 2013, Dassault Systèmes SolidWorks Corp., Waltham, MA). The parameters used are based on measured dimensions of an actual Steadicam® Scout™ stabilizing arm (Table 1).

The Steadicam® Scout™ stabilizing arm can be adjusted to support various load masses (different cameras and accessories) by turning two screws in each arm (Fig. 1(*c*)). This adjustment is called the "lift" of the stabilizing arm [21], and we use this terminology to describe the spring lever arm. The mass of the stabilizing arm mechanism considered is 4.08 kg, and this mass was assumed to be equally split between each arm segment. In this study, the a_1 adjustment of the "upper arm" was set to be 0.00635 m greater than the a_2 adjustment of the "forearm," so the upper arm would support the weight of the forearm and the load.

The Steadicam® Scout™ uses metal coil extension springs. We assume that these springs are linear and made of "music wire," a common metal extension spring material [20]. We estimated the spring stiffness k using approximate measurements (Table 1) and standard extension spring design equations [20]

Table 1 Measured parameters of the Steadicam® Scout™ stabilizing arm

Parameter	Measured value from Steadicam® Scout™ arm
Net mechanism mass, m	4.08 kg
Upper arm lift adjustment, a_1	0.0229–0.0457 m
Forearm lift adjustment, a_2	0.0178–0.0394 m
Linkage length, L	0.203 m
Other mechanism lengths, L_1, L_2, L_3	0.0635 m, 0.1905 m, 0.1334 m
Vertical linkage shaft height, H	0.073 m
Wire diameter, d	0.00493 m
Outer diameter, OD	0.0356 m
Number of coils, N_b	18
Nominal spring length, L_n	0.191 m
Music wire modulus of elasticity, E	193×10^9 pa [20]
Music wire modulus of rigidity, G	80×10^9 pa [20]
Estimated spring stiffness, k	11,733 N/m
Estimated spring pretension length, L_p	0.0381 m
Estimated spring free length, L_0	$L_0 = L_n - L_p = 0.1649$ m
Estimated spring damping, b	100 N s/m

$$D = \mathrm{OD} - d = 0.0306 \text{ m} \tag{6}$$

$$N_a = N_b - \frac{G}{E} = 17.6 \tag{7}$$

$$k = \frac{d^4 G}{8D^3 N_a} = 11733 \frac{N}{m} \tag{8}$$

Extension springs are typically designed to have a pretension when unstretched. To simulate this, we added an estimated spring pretension force [19] divided by the spring stiffness (Table 1) to the approximate unstretched spring free length L_0.

The simulation data was processed using MATLAB (MathWorks, Natick, MA). The damped natural frequency of the stabilizing arm was calculated using the logarithmic decrement method [11]. The natural frequency was approximately equal to the damped natural frequency because the damping ratio for all simulations was less than ~0.05.

3 Stabilizing Arm Mechanism Behavior

3.1 Minimizing Natural Frequency and Spring Displacement. The relationship between the spring deflection and the natural frequency of the stabilizing arm mechanism (Fig. 2(*b*)) is quite different in shape and slope from the relationship for a linear spring–mass–damper system (Fig. 2(*a*)). The stabilizing arm mechanism can achieve very low natural frequencies between 0.2 Hz and 1.2 Hz with relatively small spring deflections (less than 0.0762 m), enabling relatively stiff, high force, and robust metal coil springs to be used instead of a long travel spring.

3.2 Spring Stiffness and Load Mass. The spring stiffness affects the range of load mass values that can be supported (Fig. 3(*a*)), but does not affect the basic relationship between the natural frequency and static deflection of the mechanism (Fig. 3(*b*)). The spring stiffness should be chosen to support the desired range of load masses based on the other design parameters.

3.3 Lift Adjustment. The natural frequency of the stabilizing arm and the load mass range decreases as the lift adjustment a_1 and a_2 values decrease (Fig. 3(*d*)). The highest forearm lift adjustment a_2 supports all of the load masses tested from 1.81 kg to 13.6 kg, but results in the highest natural frequencies. The lowest natural frequencies are achieved, when the vertical static deflection of the load mass is negative, or below the horizontal, and the springs are most stretched (Fig. 3(*c*)).

3.4 Linkage Length. Increasing arm linkage length decreases the range of load masses that can be supported, increases the static deflection range (Fig. 3(*e*)), and decreases the natural frequency of the mechanism (Fig. 3(*f*)).

3.5 Spring Free Length. Decreasing the unstretched spring free length l_0 shifts the range of load masses that can be supported to larger values (Fig. 3(*g*)) and significantly reduces the natural frequency of the load throughout the range of vertical static deflections (Fig. 3(*h*)).

4 Discussion

In general, the design of stabilizing arm mechanisms is a balance between achieving a low natural frequency, an acceptable range of load masses, and a desired range of motion while limiting the spring stress and the overall mechanism size and weight.

4.1 Minimizing the Natural Frequency. A clear result which could improve all stabilizing arms is to minimize the unstretched spring free length l_0. This would minimize the natural frequency and effective stiffness of all stabilizing arms such that minimal force is required to position the load and provide the best vibration isolation. Minimizing the free length of the spring to 0 m would result in a "zero free length spring" that could achieve "zero stiffness," requiring the minimum amount of force to move the load mass through a continuous range of equilibrium positions [1]. However, it is difficult to achieve this idealized configuration because making compact springs or effective spring mechanisms that have a zero effective free length is challenging [1], and the mechanism becomes highly sensitive to load mass changes.

There are physical constraints on the lower bound of unstretched spring free length l_0 values, because decreasing the spring free length increases the total spring deflection (static and dynamic) throughout the range of motion of the stabilizing arm. Metal coil springs have a certain allowable deflection to limit the stresses in the spring, and the allowable deflection tends to decrease as the spring stiffness increases [19,20]. To obtain larger spring deflections, one could add a multiple lower stiffness springs in parallel. In general, the designer must carefully consider the total amount of spring deflection throughout the mechanisms' range of motion to ensure that the spring does not exceed allowable stress limits to achieve a useful spring life.

Reducing the lift adjustments a_1 and a_2 will tend to reduce the vertical natural frequency, but will also reduce the range of load masses that can be supported. Increasing the spring stiffness with small lift adjustments could be a useful strategy to minimize the natural frequency of the mechanism. The lift adjustments can also be used to change the vertical equilibrium position of the load, and the lowest natural frequencies are achieved, when the load is statically supported below the horizontal.

4.2 Equilibrium Position and Load Mass Adjustment. To adjust the static equilibrium position of the load mass, a stabilizing arm could allow the user to vary the unstretched spring free length l_0, the lift adjustments a_1 and a_2, and the spring stiffness k. Since the unstretched spring free length l_0 should be minimized and the spring stiffness k can be difficult to change directly, adjusting the lift values a_1 and a_2 is the best choice to change the static equilibrium position of the load mass.

The lift adjustments are relatively simple parameters to adjust because a_1 and a_2 can be readily varied using a screw-based mechanism. If the lift adjustments could be decreased to 0 m (coincident with the lower linkage pivot), the springs would pull along the linkage and would not support a load. If the lift adjustment is maximized, the stabilizing arm can support the largest

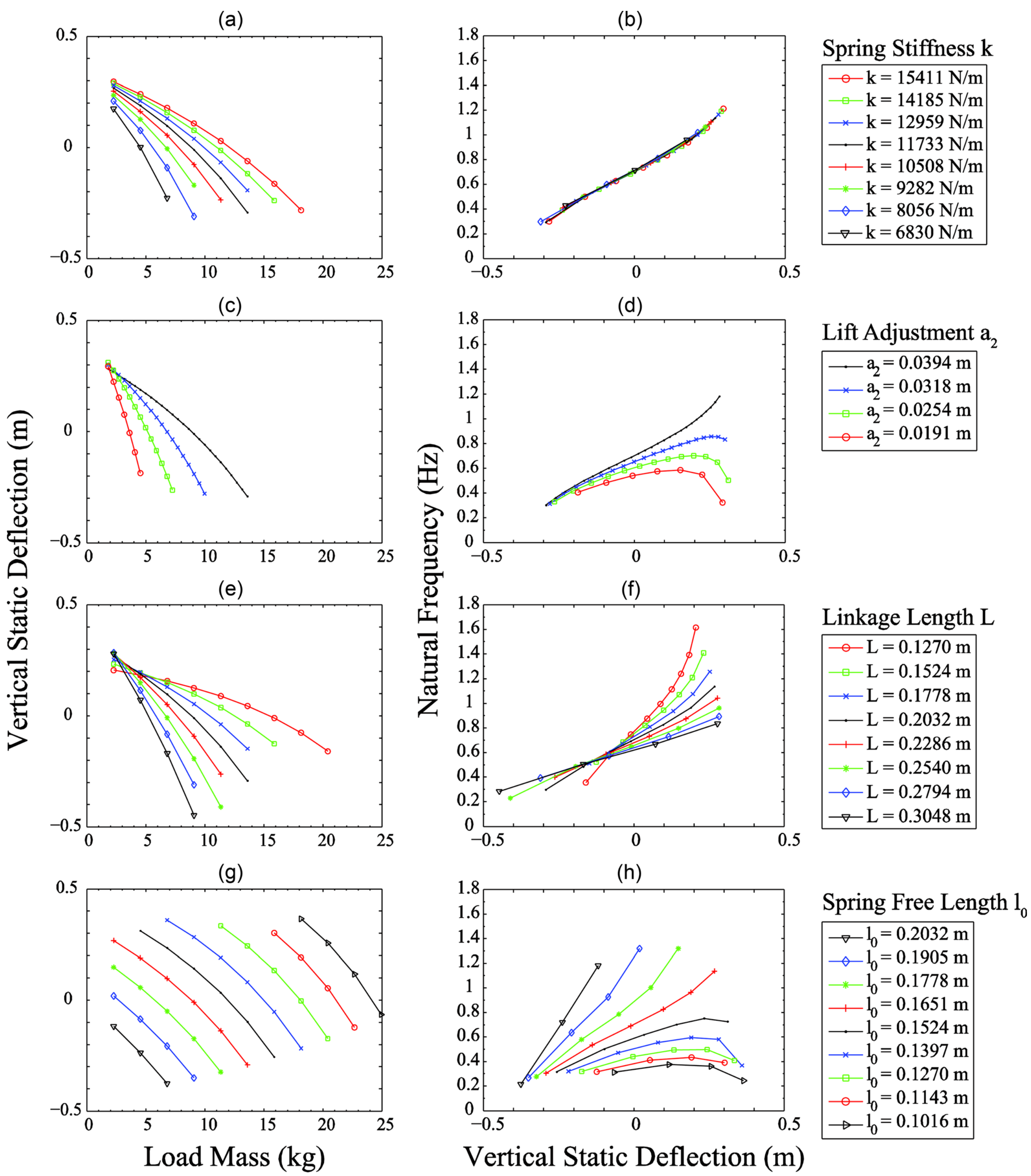

Fig. 3 Increasing the spring stiffness *k* increases the range of load mass that can be supported (*a*), but does not affect the relationship between the natural frequency of the mechanism and the static deflection of the load mass (*b*) ($L = 0.2032$ m, $l_0 = L - 0.0381$ m, $a_2 = 0.0394$ m). The lift adjustment a_2 provides a useful means to change the equilibrium position and to adjust a stabilizing arm for different load masses (*c*), but it is best to minimize the lift adjustment a_2 to minimize the natural frequency of the mechanism (*d*) ($L = 0.2032$ m, $l_0 = L - 0.0381$ m, $k = 11{,}733$ N/m, $a_1 = a_2 + 0.00635$ m). Shorter arm linkage lengths *L* are able to support larger load masses (*e*) compared to longer arm linkage lengths, but increase the natural frequency of the mechanism (*f*) ($l_0 = L - 0.0381$ m, $a_2 = 0.0394$ m, $a_1 = a_2 + 0.00635$ m, $k = 11{,}733$ N/m). Decreasing the spring free length l_0 enables the mechanism to support larger load masses (*g*) and significantly reduces the natural frequency of the mechanism (*h*) ($L = 0.203$ m, $a_2 = 0.0394$ m, $k = 11{,}733$ N/m).

range of load masses. In effect, adjusting the lift of the arm changes the mechanical advantage of the pretensioned springs. If frequent adjustment is necessary to support variable loads, the lift adjustment could be actuated with a motor and screw assembly.

The spring stiffness can be designed to support the desired range of load mass depending on the other parameters. Adjusting the spring stiffness of the stabilizing arm mechanism could be relatively simple, if the springs are external to the linkages and the springs are not very stiff, as in the WREX [3,4]. If stiffer springs are located inside the stabilizing arm, as in the Steadicam®, it is more challenging for a user to change the spring stiffness.

4.3 Stabilizing Arm Range of Motion. Longer linkage lengths will increase the overall range of motion of the load mass. This may be an important consideration for certain applications, such as positioning a camera, a tool, or an arm about its vertical static equilibrium position. Longer linkage lengths also increase the physical envelope of the device and reduce the range of acceptable load masses. If the linkage length cannot be made longer to increase the range of motion, then multiple shorter stabilizing arm segments can be attached in series.

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